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Product architecture modularity implications for operations economy of green supply chains

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ABSTRACT

The role of product architecture modularity is commonly in increasing product reusability and minimizing waste. This paper designs a decision support system to determine optimal product architecture modularity in closed loop supply chains. The objective is to investigate if remanufacturing and modular upgrading is appropriate at certain periods and in modules. The optimization model is tested under several production yield scenarios in order to determine manufacturing and remanufacturing capacity and production line scheduling under process yield uncertainty. The implications of product architecture modularity for operations economy of green supply chains are discussed in terms of their theoretical and managerial aspects.

1. Introduction

There is an environmentally conscious trend in supply chain management when considering operations sustainability. Operations sustainability includes pollution-free energy sources, renewable resources and policies (Linton et al., 2007). The implications of sustainability for the operationalization of supply chain management are to achieve the greener supply chains, to include the impact of manufacturing operations on the environment in terms of waste (all forms), energy use, and resource use (material consumption). Beamon (1999) suggests that the traditional supply chains networks design must be extended to include mechanisms for reverse logistics. The extension requires the inclusion of product design and material sourcing/selection into traditional supply chains activities in order to make environmentally friendly product specifications and to cover adequately aspects and facets (product, process and environment) of green supply chains (Srivastava, 2007). The analysis of the entire life cycle effects of all products and processes is now necessary to encapsulate those three facets of more environmentally responsible supply chains by reducing carbon footprint (Petersen et al., 2005; Waage, 2007; Ellram et al., 2008).

A more environmentally responsible supply chains needs to follow international standards for environment such as ISO 14000 that require supplier assessment for achieving sustainable business and environmental quality improvement. While buyers and transporters could implement green purchasing, green manufacturing/material management, green distribution/marketing, reverse logistics and make or buy decision (Sarkis, 2003; Hervani and Helms, 2005), proactive supplier involves in various activities of closed loop supply through green product design in order to maximize product reusability and minimize waste. In product design, product architecture modularity to be an alternative solution to achieve both green product design objectives by offering common interfaces among components.

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The objective of this paper is to present mathematical modeling and solution algorithm aspects to cover three facets of more environmentally responsible product, process and supply chains. By focusing on closed loop supply chains, we facilitate further study and research on green product design integration into closed loop supply chains. Green product design is represented by a generic model of product architecture modularity, which is measured by how substitutable a module or product against other product family with the same product portfolio. Supply chain profit, manufacturing lead times and product recycle ratio are performance indicators of the closed loop supply chains.

1.1. Product architecture modularity implications for product recovery

The objective of modular product architecture is to develop detachable modules and interfaces which enable an easy way to develop new product variants, simple assembly and disassembly, and therefore improve product recyclability and life cycle (Gu et al., 1997). With respect to environmental impact, the degree of modularization is improved by redesigning module interfaces (Smith and Yen, 2010; Tseng et al., 2008) that allows more frequent reuse of modular components. Xerox reuses its printer mechanical parts (Fernandez and Kekale, 2005) by modularization that is suitable for product recovery/refurbishing/reuse (Johnson, 1998).

From a purchasing point of view, Fernandez and Kekale (2005) pointed out that product remanufacturing complicates purchasing by adding a supply source from the remanufacturing firm and an internal demand source from product return. Lower product architecture modularity can cause problems for purchasing personnel due to unexpected need for components. Purchasers need to find such components from broker services at higher component cost or otherwise the manufacturer must stop the production line.

1.2. Product architecture modularity implications for supply chain sustainability

With considering supply chain sustainability, Linton et al. (2007) suggest product architecture modularity for increasing product reusability and minimizing the environmental impact over product useable life (Karna and Heiskanen, 1998). The assessment of product architecture modularity on supply chain sustainability should be aligned with cost–benefit analysis (Kim et al., 2006; Kara et al., 2007; Zhu et al., 2008) and the trend of customer wants for after life service and recyclable products (Ellinger et al., 1997). Mutha and Pokharel (2009) show that a higher level of returned capacity lowers the total supply chain and product design costs. Thus, the effect of return capacity for capacity planning in the remanufacturing operations can be comprehensively analyzed (Vlachos et al., 2006).

1.3. Product architecture modularity implications for supply chain flexibility

Product architecture modularity can be implemented in supply chains with product, volume, launch, access and market flexibility (Vickery et al., 1999). Product and volume flexibility could reduce the capacity investment of multi-product manufacturing (e.g., electronic manufacturing (Nakamoto, 2003), airplane manufacturing (Lunsford, 2007)). Launch flexibility determines the production capacity after observing demand realization and the market price. The introduction of product substitutability in a coordinated supply chain generates market and access flexibility.

Market flexibility is necessary to reduce mismatch between supply and demand, which often reduces supply chain profit. While capacity and technology decisions in the manufacturing industry have to be as early as 5 years from the planned manufacturing date (Fleischmann et al., 2006), flexible production line scheduling is a cheaper way to reduce setup time and to achieve volume flexibility (Greenberg, 2001). Volume flexibility needs organizational flexibility (Duclos et al., 2003). An alternative solution such as process retrofitting is pursued by, for instance, by BMW (Edmondson, 2005) and Ford (MacKintosh, 2003), in order to reduce setup time and to achieve volume flexibility. These firms reduce demand uncertainties by making their production lines more volume flexible (both upstream and downstream), and designing products with modular product architecture.

1.4. Conclusion of the discussion

Agrawal and Ülkü (2013) view the present idea of using product architecture modularity in green supply chains as not being well and generally understood, and therefore may lead to least efficient solution to green supply chains. One reason is that there is no investigation from past contributions (e.g., Keene et al., 2012; Mutha and Pokharel, 2009) about how the economic measure of modularity degree is counted in order to meet both economic and environmental criteria. With regard to the economic measure of product modularity degree, the level of product substitutability has great implications for technological systems that are modularly upgradable.

Green supply chains must be sustainable by having the capability of hedging against fluctuations in internal (i.e., process yields, product failures, etc.) and external processes (i.e., demand changes, customer return variations, etc.) (Guide et al., 1997a). Adaptive operations planning and supply chain design would cover short (adaptivity into operation planning by making feasible production routings after resolving endogenous uncertainty) and long term changes (i.e., product design changes, process technology changes, etc.) at any time and adjust operations scheduling accordingly (e.g. Iyer and Grossmann, 1997). Both plannings determine supply chain profitability at lower environmental impacts.